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Emergy-based Ecological Benefits Evaluation of Green-Blue Infrastructure in Sponge Residential Community

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ABSTRACT

The Green-Blue infrastructures in sponge residential communities have important ecological benefits but are still lack of systematic evaluation methods. This study proposes an emergy-based classification and evaluation method for four types of Green-Blue infrastructures, including forest type, wetland type, grassland type, and special type. 20 typical sponge residential communities in 7 cities of China are surveyed. The results show that wetland type infrastructures (including biological retention pond and rainwater garden) can provide the highest ecological benefit per unit area. There is obvious spatial heterogeneity of GBIs' ecological benefits. The results show that, compared with north cities, the construction of GBIs can provide higher ecological effects in south cities. The donor-side method can provide new ideas and references for the assessment of sponge residential communities.

Keywords: emergy method, Green-Blue infrastructure, ecological benefits.

1. INTRODUCTION

Green-Blue infrastructure (GBI) plays a vital role in sustaining natural ecological processes in urban environments and contributing to the health and quality of life. The Land Conservation Report of Florida describes green infrastructure as a water-soil coupling system that plays an important role in maintaining nature's circulation and protecting the diverse natural resources for human well-being[1]. With the development of society and the multiple additional ecosystem services it provides, the concept of GBI has become more widespread. The GBI is based on the city's biological components. Specifically, blue infrastructure refers to reservoirs, lakes, wetlands and waterways, etc., that plays a key role in urban environment especially in the purification of water, flood mitigation and replenishment of groundwater[2]. Urban parks, woodland, green roofs and the naturally or artificially occurring green areas are part of the green infrastructure[3]. It offers critical ecosystem services, for instance, air quality improvement, microclimate control and urban landscape beautification[4-5]. The traditional infrastructure, also known as grey infrastructure, is focused on abiotic components, encompassing roads, highways and water-transporting or water-treatment systems. However, urban issues like pollution, floods, habitat destruction and traffic congestions have shown that conventional grey infrastructure is weak and unable to deal with climate change impacts[13]. Therefore, major focus has been put on development of robust and more adaptable infrastructure systems. The GBI is currently seen as an effective way of promoting urban ecosystems and human well-being[6].

There have been currently models and methods that can be used to evaluate GBI's ecological benefits, such as InVEST, EcoMetrix, GVC and emergy method. The InVEST model is a popular tool for accounting and mapping multi-scale ecosystem services. It's simple and easy to use, approved by experts, multi-functional and adaptable to different spatial scales and scopes[7]. EcoMetrix is a GIS-based tool that can be used to evaluate the relative level of ecosystem services and the amount of improvement. It requires supplementary data on site investigations and is more applicable to small scale system[7]. The National Green Value Calculator (GVC) is designed for site scale (such as green roof, rain garden, sidewalks). It can be used to compare the performance, cost, benefit of green infrastructure and implement the rainwater management evaluation with a long time span (such as 50 years). However, it is more suitable for event simulation and it only provides US local database[8]. Emergy analysis is a thermodynamic based evaluation method that uses embodied solar exergy (emergy) as a benchmark to convert different types of incomparable energies into a common unit (sej) for analysis and comparison[10]. The emergy method has been mainly applied to a single ecosystem or multi-scale regions such as at the provincial or national level, and its methodological framework has been relatively completed. The key advantage of emergy is that it accounts the donor-type value, which is determined by the production process and not by human's preferences or willingness to pay. In recent years, many emergy researchers turn their interests on the ecological benefit analysis of green infrastructures. For instants, Pulselli *et al*. used the emergy accounting evaluation method to evaluate the emergency status of green infrastructure such as vertical greening system (VGS). The evaluation mainly included environmental costs, landscape configuration, and ecosystem services[11]. Law *et al.* used emergy analysis to compare the sustainability and energy input differences of rainwater gardens, green roofs, porous pavements and tree plantings in green infrastructure. The study concluded that green roofs and tree plantations were more sustainable, and the energy input of porous pavements was relatively high, which provided a reference for the selection of green infrastructure in urban housing[9]. Fu and Li used emergy analysis methods (including 5 indicators such as emergy output and renewable percentages) to evaluate the sustainability of rain gardens, grass swales, green roofs, constructed wetlands, and permeable pavement [12].

Previous studies have reported that the emergy method has strong applicability in the accounting of GBI. However, the application of emergy method still lacks a framework in its application to GBI ecosystem services valuation. In fact, economic approaches are still prevailing. This study aims to fill this research gap. In particular, this research systematically divides GBI into four types and develops its framework for small-scale ecological emergy evaluation. At the same time, the spatial dependence and heterogeneity have existed all the time in the GBI evaluation in different sponge cities. Thus, 7 typical sponge cities in Northern and Southern China have been selected to conduct evaluation, and explore the performance of their GBIs. This study will provide some policy recommendations for the sponge cities management.

2. METHODS

2.1 The evaluation framework and classification system

Modeled on the principle of natural ecosystem classification, this study divides Green-Blue infrastructures into wetland type (Type-A), grassland type (Type-B), special type (Type-C) and forest type (Type-D) based on the construction requirements and the ecosystem services that produced. For better analysis and comparison, the typical infrastructures are classified as A1-biological retention pond, A2-rainwater garden, B1-sunken green space, B2- planting grassland, B3-green roof, C1-permeable pavement, C2-seepage well, C3-water storage tank, D1-urban forest and D2-street tree with permeable pavers.

GBIs, just like the nature systems, can provide ecosystem services based on the changes in ecological flows and storages. However, due to its man-made characteristics and the construction on the urban hardened ground, the ecosystem services generated by GBIs are not completely equivalent to the natural ecosystem. Taking type-A as an example, the small ecosystem of biological retention pond can provide the ecosystem services like biomass increase, carbon sequestration, groundwater recharge, surface water regulation, air purification and microclimate regulation. These categories and components are assigned to the different ecosystem types according to the scheme reported in Table 1.

Table 1. Ecosystem services provided by GBIs

Type	Ecosystem services					
	Biomass increase	Carbon sequestration	Ground water recharge	Surface water regulation	Air purification	Microclimate regulation
A1	○	○	○	○	○	○
A2	○	○	×	○	○	○
B1	○	○	○	○	○	×
B2	○	○	○	○	○	×
B3	○	○	×	○	○	×
C1	×	×	○	×	×	×
C2	×	×	○	○	×	×
C3	×	×	×	○	×	×
D1	○	○	○	○	○	○
D2	○	○	○	○	○	○

2.2 *Emergy-based accounting methods*

The ecosystem services accounting techniques are detailed below:

- *Biomass increase*

$$E_{mNPP} = Max(R_i) \tag{1}$$

Among them, E_{mNPP} is the required emergy value (sej) for increasing NPP, and R_i refers to the input amount of all renewable emergy values in the area. The R_i includes the sum of solar, geothermal emergy, wind emergy, and the sum of other renewables (e.g.: rain chemical energy, irrigation water).

- *Carbon sequestration*

The process of photosynthesis is generating organic matter and fixing carbon dioxide, but the amount of carbon sequestered is only one-half of the biomass, and the solid state of the ecosystem is $\frac{1}{2}(\Delta B + \frac{B}{T})$. The carbon sequestration rate is used in the calculation in this study. Therefore, the calculation formula is:

$$E_{m(CF)} = v \times S \times UEV_{csi} \tag{2}$$

$$UEV_{csi} = \frac{E_{smNPP}}{NPP} \tag{3}$$

Among them, $E_{m(CF)}$ is the emergy value required for carbon sequestration (sej); v is the carbon sequestration rate, which is the amount of carbon sequestration per unit area of GBI per year ($g \cdot m^{-2} \cdot a^{-1}$); ***S*** is the infrastructure area (m^2); UEV_{csi} is the transformity of carbon sequestration ($sej \cdot g^{-1}$); E_{smNPP} is the emergy value required to increase NPP per area (sej); *NPP* is the biomass of this type of GBI (g).

- *Surface water regulation*

$$E_{m(WSR)} = M_{water} \times UEV_{water} \tag{4}$$

$$M_{water} = S \times d \times \rho \tag{5}$$

The density of water ρ is $1000 kg/m^3$, UEV_{water} is the transformity of water, M_{water} is the total water storage (m^3), *S* is the area of the infrastructure (m^2), and *d* is the depth of runoff (m), which is actually designed by the specific infrastructure.

- *Groundwater recharge*

$$E_{gw} = R \times \rho \times S \times k \times UEV_{gw} \tag{6}$$

Among them, E_{gw} is the emergy value (sej) required to recharge the groundwater; *R* is the annual precipitation in the study area ($m \cdot yr^{-1}$); ρ is the water density ($kg \cdot m^{-3}$); *S* is the infrastructure area (m^2); *k* is the precipitation infiltration recharge coefficient; UEV_{gw} is the transformity of groundwater ($sej \cdot g^{-1}$). Some GBIs have this ecosystem service due to the permeable ground but some are not, if they are constructed on hardened ground or roof.

- *Air purification*

GBIs can purify SO_2, CO, O_3, PM_{10}, $PM_{2.5}$, fluoride and nitrogen oxides and other air pollutants, based on different vegetation choices. In consequence, it can reduce the loss of human health and ecological resources caused by air pollution. Specifically, there are two aspects:

Reduction in human health loss:

$$E_{m(HM)} = \sum (M_i \times S \times DALY_i \times \tau_H) \tag{7}$$

Reduction in ecological resource loss:

$$E_{m(ER)} = \sum (M_i \times S \times PDF(\%)_i \times E_{Bio}) \tag{8}$$

Among them, $E_{m(HM)}$ is the emergy value (sej) of the reduction in human health loss after the purification of air pollutants; M_i is the ability to purify the *i*-th air pollutant ($kg \cdot hm^{-2} \cdot a^{-1}$); S is the area of the infrastructure (hm^2); $DALY_i$ is the influencing factor of the *i*-th air pollutant; τ_H is the ratio of the total regional medical expenditure per capital ($sej \cdot person^{-1}$); $E_{m(ER)}$ is the emergy value of the reduction of natural resource loss after air pollutant purification (sej); $PDF(\%)_i$ is the potential extinction ratio of species affected by the *i*-th air pollutant; E_{Bio} is the emergy value required by the species in the study area, which is measured by the emergy value of regional renewable resources (sej).

$$E_{m(AP)} = E_{m(HM)} + E_{m(ER)} \tag{9}$$

- *Microclimate regulation*

$$E_{mE} = E_{EW} \times S \times \rho_w \times UEV_{EW} \tag{10}$$

E_{mE} is the emergy value required to regulate temperature and humidity (sej); E_{EW} is the average annual evaporation (m); *S* is the area of the study area (m^2); ρ_w is the density of water ($g \cdot cm^{-3}$); UEV_{EW} is the transformity of water vapor ($sej \cdot g^{-1}$).

It is worth to be mentioned that, the GBI actual area of type-B2 is not equal to the area covered by green vegetation, so the area used in the equations needs to be calibrated. According to the standards of the "Technical Guideline for Sponge City Construction", the minimum area correction coefficient of the planting grassland (type-B2) in buffer strip and grassed swales should be set as 0.8, that is,

$$S' = 0.8 S_{facility} \tag{11}$$

2.3 Data sources

In this study, 20 sponge residential communities in 7 cities (including Beijing, Qingdao, Changde, Nanning, Pingxiang, Xiamen and Wuhan) are selected. GBIs data are collected through field sampling and monitoring.

3. RESULTS

As shown in Figure 1, the emergy-based ecosystem services values of different GBIs in 20 sponge residential communities have been calculated. The average values are used if the values of same GBIs have small differences. The results show that the largest ES value are wetland type GBIs, followed by forest type and grassland type, and the smallest is special type.

The ESVs per area of wetland type infrastructures (A1, A2) is significantly higher than other types, mainly because of the high ES of surface water regulation. The mean ES values per area of forest type (D2) and grassland type (B1, B2, B3) are very close, but the formers are slightly ahead, and their ESVs per area are only 39.2% and 28.9% of wetland type GBIs respectively. The major contribution of the ESVs per area in grassland and forest type infrastructures is increasing biomass, and the ESVs per area is close to that of wetland type. Obviously, each single ESV of the forest type infrastructure is higher than that of grassland type, especially in microclimate regulation. The special type infrastructures only have few ESVs per area (about 1.17% compare with the wetland type) and the major contributions are surface water regulation and groundwater recharge.

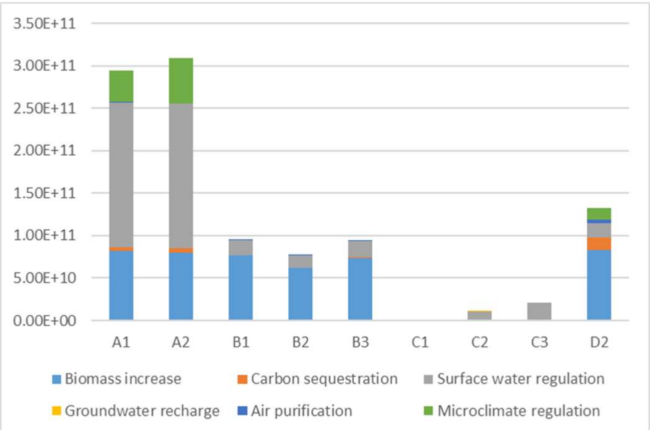

Figure 1. Emergy-based ecosystem services values per area of the GBIs (A1-biological retention pond, A2-rainwater garden, B1-sunken green space, B2- planting grassland, B3-green roof, C1-permeable pavement, C2- seepage well, C3- water storage tank, D1-urban forest and D2-street tree with permeable pavers)

Further, the whole ESVs of each sponge residential community in different cities are calculated, based on the different proportions between ecological land and residential land. The results in Figure 2 show that special type infrastructures contribute the most of the proportions (in one sponge residential community, it is close to 98%), even if it provides the minimum ESV per area. That means in the current sponge community renovation, the satisfaction of cost factors and individual functions (such as surface water regulation) is the first requirement. Besides, the grassland type infrastructures are the second choice. There is almost no forest type.

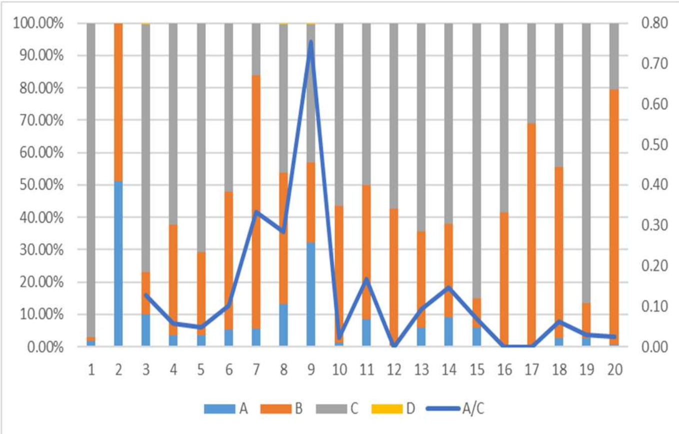

Figure 2. The proportion of the four types ecological lands in 20 sponge residential communities (A-wetland type, B-grassland type, C-special type; D-forest type infrastructures, A/C means the ratio between the wetland type infrastructure area and the special type infrastructure area.

Previous results of ESVs per area are calculated the mean ES values of the same type of GBIs in 20 sponge residential communities. If we compare the individual ESVs results, they show obvious spatial heterogeneity. Geographically, the selected cities can be divided into north (such as Beijing and Qingdao) and south cities (such as Nanning, Pingxiang, Xiamen, Changde and Wuhan). As shown in Figure 3, in terms of wetland type infrastructures, the total ESV per area in the southern community are 1.64 times larger than that in the northern community. The main reason might be that the more abundant rainfall area, the more obvious ESVs of surface water regulation function of wetland. The north cities are located between 400mm and 800mm precipitation curves and the south cities are located in the area of 800mm precipitation curve. Concerning on the special type infrastructures, the ESV per area in the southern community is 2.36 times larger than that in the northern community. That shows the spatial heterogeneity of soil reflects upon the ecosystem services of surface water regulation and groundwater recharge. The results show that, compared with north cities, the construction of GBIs can play better ecological effects in south cities.

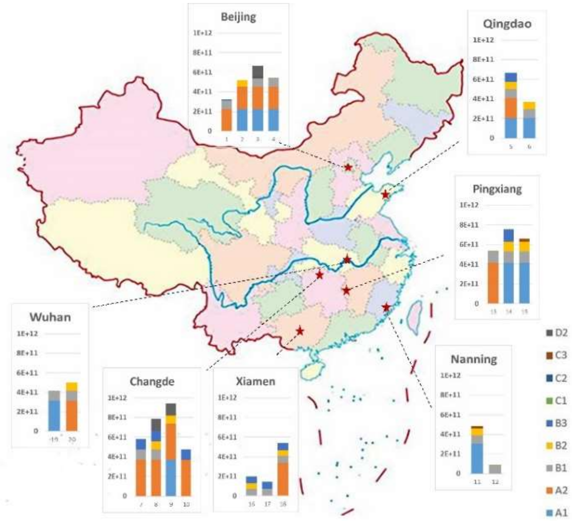

Figure 3. Ecological effects in 20 sponge residential communities of 7 cities (A1-biological retention pond, A2-rainwater garden, B1-sunken green space, B2- planting grassland, B3-green roof, C1-permeable pavement, C2-seepage well, C3-water storage tank, D1-urban forest and D2-street tree with permeable pavers.)

4. DISCUSSION

It can be observed that there is a certain difference between the ESVs of various infrastructures and the actual application requirements, and the community residents are not just inclined to use the infrastructures that provide more ecosystem services. The reason behind this is that the sponge community renovation is subject to a variety of factors including community areas, investments, residents preference and construction purpose. So more consideration is given to the actual situation of the sponge community renovation. Although the ecosystem services provided by special type infrastructure are simple, they are widely used because of their simple construction, low investment and ability to effectively solve the problem of rainwater retention. The wetland type infrastructures can bring much higher ecosystem services, but due to the high construction and maintenance costs, land occupation and mosquito breeding, they are not being used on a wider scale.

Even if only 7 cities in China are selected, the spatial heterogeneity of ESV of GBIs can still be found. The ecological benefits of GBIs in southern China are higher than that in north. Therefore, it can be inferred that differences in natural factors such as rainfall, soil viscosity and terrain topography will have a significant impact on the ecological benefits of GBIs, which should be taken into account and paid attention to in the construction and evaluation of infrastructures.

5. CONCLUSION

This study constructed a donor-side accounting methodology for evaluating the ecological effects of 20 sponge residential communities in 7 cities of China. The results show that wetland type infrastructures can provide the highest ecosystem services per unit area (the major contribution is surface water regulation); forest and grassland type infrastructures can provide 39.2% and 28.9% ESVs per area comparing with wetland type (the major contribution is biomass increase); special type infrastructures can only provide 1.17% ESVs per area comparing with wetland type, but it's really the most widely used GBIs.

Besides, there is obvious spatial heterogeneity of GBIs' ecological benefits. The results show that, compared with north cities, the construction of GBIs can provide higher ecological effects in south cities. Therefore, the reconstruction of sponge community needs to be designed and constructed according to local conditions and combined with various requirements

The establishment of the emergy-based systematic method is helpful to the quantitative evaluation of the sponge community and provide some reference advice for the planning, construction and evaluation of the sponge city.

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